# Constraints on Mantle Plume Melting Conditions in the Martian Mantle Based on Improved Melting Phase Relationships of Olivine-phyric Shergottite Yamato 980459

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**Introduction:** Martian meteorite Yamato 980459 (hereafter Y98) is an olivine-phyric shergottite that has been interpreted as closely approximating a martian mantle melt [1-4], making it an important constraint on adiabatic decompression melting models. It has long been recognized that low pressure melting of the Y98 composition occurs at extremely high temperatures relative to martian basalts (1430 °C at 1 bar), which caused great difficulties in a previous attempt to explain Y98 magma generation via a mantle plume model [2]. However, previous studies of the phase diagram were limited to pressures of 2 GPa and less [2, 5], whereas decompression melting in the present-day martian mantle occurs at pressures of 3-7 GPa, with the shallow boundary of the melt production zone occurring just below the base of the thermal lithosphere [6].

Recent experimental work has now extended our knowledge of the Y98 melting phase relationships to 8 GPa. In light of this improved petrological knowledge, we are therefore reassessing the constraints that Y98 imposes on melting conditions in martian mantle plumes. Two recently discovered olivine-phyric shergottites, Northwest Africa (NWA) 5789 and NWA 6234, may also be primary melts from the martian mantle [7, 8]. However, these latter meteorites have not been the subject of detailed experimental petrology studies, so we focus here on Y98.

**Phase Diagram:** Over the last several years, experiments at the Johnson Space Center have constrained both the phase diagram [9] (**Figure 1**) and the liquid line of descent [10] for Y98. Assuming that Y98 represents a low melt fraction (which is typically true for shergottites), the liquidus temperatures in Figure 1 should closely approximate the mantle solidus temperature when the Y98 melt was in physical contact with the material that composed the Y98 mantle source region. At low pressures (up to 1.2 GPa), the inferred mantle solidus temperature for Y98 is 300-350 °C hotter than for melting of the primitive martian mantle [11]. However, the slope of the mantle solidus in Figure 1 flattens out significantly at higher pressure, reflecting the effect of near-liquidus garnet above 5 GPa on the Clapeyron slope. The solidus is effectively constant at 1650 °C from 4-7.5 GPa. This is a crucial observation, as this is 115 °C (at 4 GPa) to just 30 °C (at 5 GPa) above the solidus in the primitive martian mantle [11]. This contrasts with the 200 °C temperature difference between the primitive mantle and Y98 solidii at 4 GPa estimated from extrapolation of the low pressure melting data [2]. Thus, while Y98 may require a modestly elevated mantle temperature for melting, it is not the daunting problem that it was once thought to be.

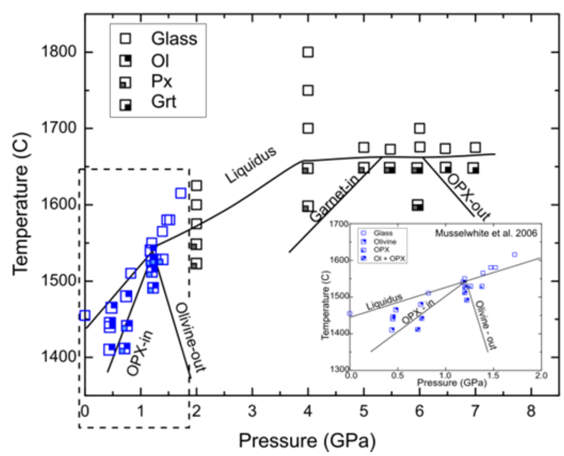


**Figure 1:** The melting phase diagram for Y98 up to 8 GPa. Experimental points below 2 GPa (blue) are from [2]. Experimental points at 2-8 GPa (black) are from [9].

**Methods:** We model mantle plume thermal structure in spherical axisymmetric geometry using a finite element mantle convection code [6, 12]. We use a strongly temperature-dependent rheology to impose a stagnant lid and assume that 50% of the total radioactivity is partitioned into the crust (the upper 50 km of the model). Adiabatic decompression melting is modeled by tracing streamlines through the melting zone [13, 14]. We calculate melting using a water under-saturated peridotite melting model [15] with two modifications. First, we replace the dry solidus

used in [15] with a piecewise linear approximation of the results in Figure 1. Second, we note that in an MgO rich system such as Y98, the effect of water on depressing the solidus is enhanced [16]. Based on melting studies of Y98 over a range of water contents [17-19], the solidus depression for a given amount of water is a factor of 2 higher in this work than in [15].

**Results:** Previous modeling of present-day martian mantle plume magmatism has been constrained by geologic observations of Amazonian volcanism rates, geochemical constraints on melt fraction and on mantle water content, and geophysical constraints on both the near-surface heat flux and the heat flux out of the core [6, 12, 14]. Based on those constraints, the thermal Rayleigh number (which measures the vigor of the mantle convective flow) is between $10^6$ and $10^7$ based on the volume-averaged mantle viscosity and the core-mantle boundary temperature is between 1700 and 1900 °C.

We adopt these values as reasonable constraints for the plume that produced the olivine-phyric shergottites. Studies of the D/H ratio of olivine-hosted melt inclusions in Y98 indicate a preferred mantle source region water content of 15-47 ppm, with an upper bound of 116 ppm water [20]. Studies of apatites in NWA 6234, another olivine-phyric shergottite that may be a mantle melt, indicate that mantle volatile contents (water, Cl, and F) are likely similar to those in the terrestrial mid-ocean ridge basalt source region [21]. We therefore consider water contents from 0 to 200 ppm for the mantle source region in this work. Any chlorine or fluorine that is present in the mantle source region will also help to lower the solidus temperature relative to its dry value [22, 23].

**Figure 2** shows the minimum required core-mantle boundary temperature to permit decompression melting in the rising plume material as a function of the water concentration in the mantle source region. The Y98 melting onset results overlap with those for onset of melting of the primitive mantle, demonstrating that it is in fact not difficult to initiate melting of the source mantle for the olivine-phyric shergottites. An important difference between the primitive mantle and the olivine-phyric shergottite mantle source region is the depth at which the onset of melting occurs. The onset of melting for the primitive mantle is near 3.8 GPa, expanding to include the range 3-6 GPa with increasing water concentration. Melting in the Y98 source mantle begins below 7 GPa and expands upward to include the 5-6 GPa multiple saturation zone (orthopyroxene and garnet) if a small amount of water is present. This multiple saturation zone therefore may have significance as a marker of melting depth. In contrast, it has proven impossible to achieve mantle plume melting near the 1.2 GPa olivine-orthopyroxene multiple saturation pressure point in the Y98 system [2].

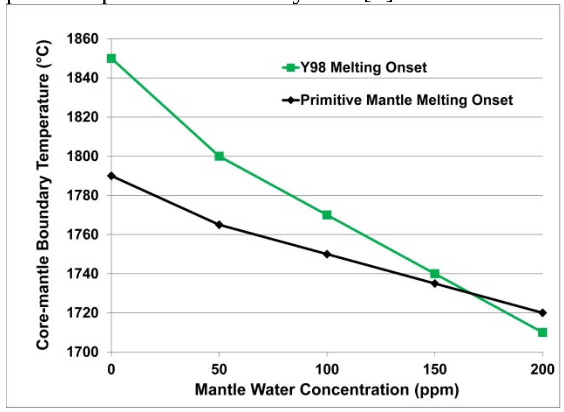


**Figure 2:** The minimum core-mantle boundary temperature required for the onset of mantle plume melting as a function of mantle source region water content at Ra=$6.1 \cdot 10^6$. The black line is for the primitive Mars solidus and the green line is for the Y98 solidus.

**References:** [1] Greshake et al., *Geochim. Cosmochim. Acta* 68, 2359-2377, 2004. [2] Musselwhite et al., *Meteoritics Planet. Sci.* 41, 1271-1290, 2006. [3] Usui et al., *Geochim. Cosmochim. Acta* 72, 1711-1730, 2007. [4] Filiberto and Dasgupta, *Earth Planet. Sci. Lett.* 304, 527-537, 2011. [5] Blinova and Herd, *Geochim. Cosmochim. Acta* 73, 3471-3492, 2009. [6] Kiefer and Li, *Meteoritics Planet. Sci.,* manuscript in review, 2016. [7] Gross et al., *Meteoritics Planet. Sci.* 46, 116-133, 2011. [8] Gross et al., *Meteoritics Planet. Sci.* 48, 854-871, 2013. [9] Usui et al., *Lunar Planet. Sci. Conf.* 44, abstract 2877, 2013. [10] Rapp et al., *Meteoritics Planet. Sci.* 48, 1780-1799, 2013. [11] Kiefer et al., *Geochim. Cosmochim. Acta* 162, 247-258, 2015. [12] Li and Kiefer, *Geophys. Res. Lett.* 34, 2007GL030544, 2007. [13] Watson and McKenzie, *J. Petrology* 32, 501-537, 1991. [14] Kiefer, *Meteoritics Planet. Sci.* 38, 1815-1832, 2003. [15] Katz et al., *Geochem. Geophys. Geosys.* 4, 2002GC000433, 2003. [16] Médard and Grove, *Con. Min. Pet.* 155 , 417-432, 2008. [17] Norris and Herd, *Lunar Planet. Sci. Conf.* 37, abstract 1787, 2006. [18] Dalton et al., *Lunar Planet. Sci. Conf.* 38, abstract 2102, 2007. [19] Draper, *Lunar Planet. Sci. Conf.* 38, abstract 1447, 2007. [20] Usui et al., *Earth Planet. Sci. Lett.* 357-358, 119-129, 2012. [21] Gross et al., *Earth Planet. Sci. Lett.* 369-370, 120-128, 2013. [22] Filiberto et al., *Chem. Geol.* 312-313, 118-126, 2012. [23] Filiberto et al., *Con. Min. Pet.* 168, 1027, 2014.